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LASER ANEMOMETRY CLOSE TO WALLS

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ABSTRACT

Schodl[1], and others, have reported the development of two-spot or transit anemometer systems. These systems appeared superficially to make unsophisticated 'time of flight' measurements. Work at Rolls-Royce[2] and Spectron Development Laboratories[3] has led to improved second generation optical systems and data processing techniques with significant advantages over fringe laser velocimeter systems in certain applications.

In this paper some advantages of transit anemometry for measuring close to walls and in periodic flows are demonstrated. The unquestioned superiority of this approach for flare rejection does not necessarily lead to longer measurement times. The more complete data gives two-dimensional velocity probabilities and shear stresses in places not easily accessible by standard techniques. Gated measurements are shown for non-stationary situations such as rotating machines and other cases not easy with backscatter fringe anemometry. The high accuracy of the technique is a clear bonus as velocities are easily measured to 0.5% and 30 arc minutes using sub-micron particles.

The high dynamic range of this device, $1\ ms^{-1}$ to $1000\ ms^{-1}$, also increases its usefulness in a number of normally difficult situations.

INTRODUCTION

Conventional real fringe laser anemometry has an impressive history of successful applications where the signal received from small scattering particles is not too seriously swamped by stray light from other sources. In many recent applications, attempts to use fringe anemometry have been frustrated by light scattered at the laser wavelength from machinery close to the sampling volume, for example, walls and blades in turbo-machines.

STRAY LIGHT REJECTION

Light scattered at wavelength other than that of the incident laser may be rejected by suitable filters; and to this end some work has been done on fluorescent mechanisms, either as a fluorescent seed where the wavelength shifted light is accepted or as a fluorescent coating to the wall in question permitting rejection of the scattered light from the wall. The former has been very successful but requires the addition of special seed and the prevention of its deposition on the surfaces which may give troublesome scatter. The latter is not very effective as the mechanism of fluorescent coating is such as to carry the active absorber in a transparent medium. Only the light which enters the medium can be absorbed. That which scatters at the surface is just as troublesome as that scattered from the surface before coating. The unsurprising behavior of some coatings is shown in Figure 1 for 45° laser incidence. The laser used was helium neon

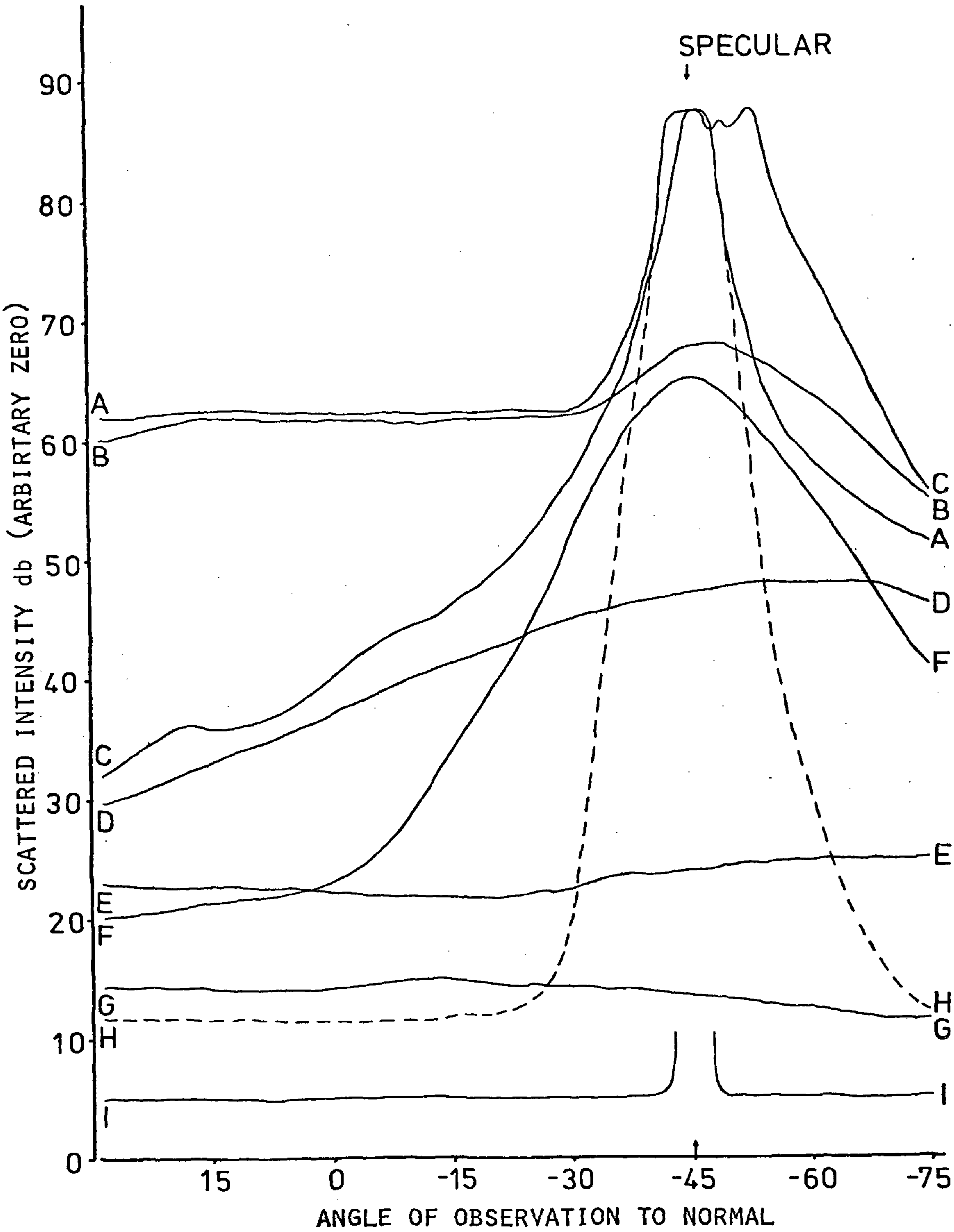

FIGURE 1. LIGHT SCATTERED FOR 45 DEGREE INCIDENCE.

and a suitable fluorescent absorber was methylene blue in gelatin -- a somewhat fragile coating not suitable for use in hostile conditions. (A carrier other than gelatin could be found.) Figure 2 shows a normally incident beam and the equivalent curves. The key to the letter identification in Figures 1 and 2 is shown in Table 1.

Table 1. Legend for Figures 1 and 2.

A	--	Sprayed Matt White Paint
B	--	Sprayed Matt White Undercoat (more Lambertian)
C	--	Machined Aluminum (milled with some blaze asymmetry)
D	--	Brushed Matt Black Paint
E	--	Candle Smoked Carbon
F	--	Sprayed Matt Black Paint
G	--	Black Velvet (delustered rayon)
H	--	Sprayed Matt Black Paint with 0.1-0.2 mm Overcoat Layer of Methylene Blue Loaded Gelatin
I	--	Clean Optical Glass

It is clear from this that stray light can be reduced by these methods, but they involve modification of the test situation which is, of course, undesirable in many cases.

GEOMETRICAL CONSIDERATIONS

Geometrical subtlety is a superior method of rejecting stray light. The correct devising of optical systems and optimal stops is not trivial. Using fringe systems ways to minimize focal depth, and hence the susceptibility to scattered light from nearby walls, are to use a wide aperture lens or to use oblique observation. The latter is very effective but is not always convenient. It is frequently impossible to accommodate windows so large that they may be used with

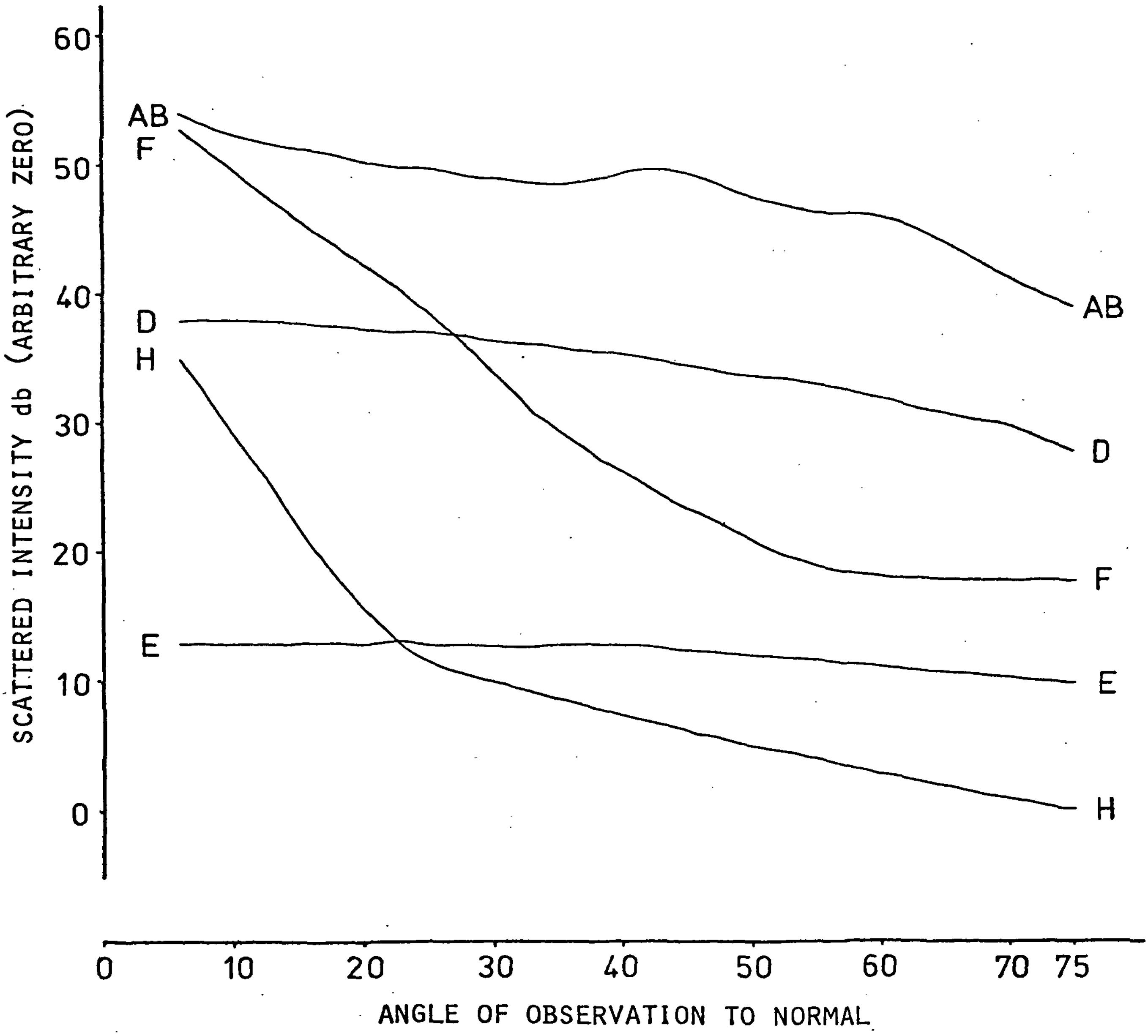

FIGURE 2. LIGHT SCATTERED FOR NORMAL INCIDENCE.

such a system. Indeed in most situations where wall flare is a problem there is a constraint to have very small windows. A coaxial backscatter system is a first choice and the use of proper stops to reject wall flare is essential.

Here a transit system has some merit since it concentrates its light into a much smaller volume -- yielding brighter light from scattering particles and reduced light from background. Let us compare two systems, fringe and transit in an attempt to make some quantitative estimates.

Firstly consider the receiving system as comprising the stops shown in Figure 3. The geometrical analysis is very simple. We know that the illumination is the highest on axis and consider the amount of light receivable from axial points -- coordinates x, measured as positive away from the detector.

In consideration of Figure 3 we may look at purely geometrical extreme rays, noting that in a real system there will be very significant effects of diffraction. Diffraction serves to smear the clean lines of Figure 3 but in no way changes its conclusions. We assume that the lens is perfectly corrected for the appropriate conjugates, but this is usually too difficult or too expensive to generate if the system is to be at all versatile. To the extent that this criterion is not met, ultimate performance will be inferior to the geometrical ideal outlined here.

We will use Ω as proportional to the total solid angle indicated by a limiting ray cone and note the formulae of Table 2 in the notation of Table 3.

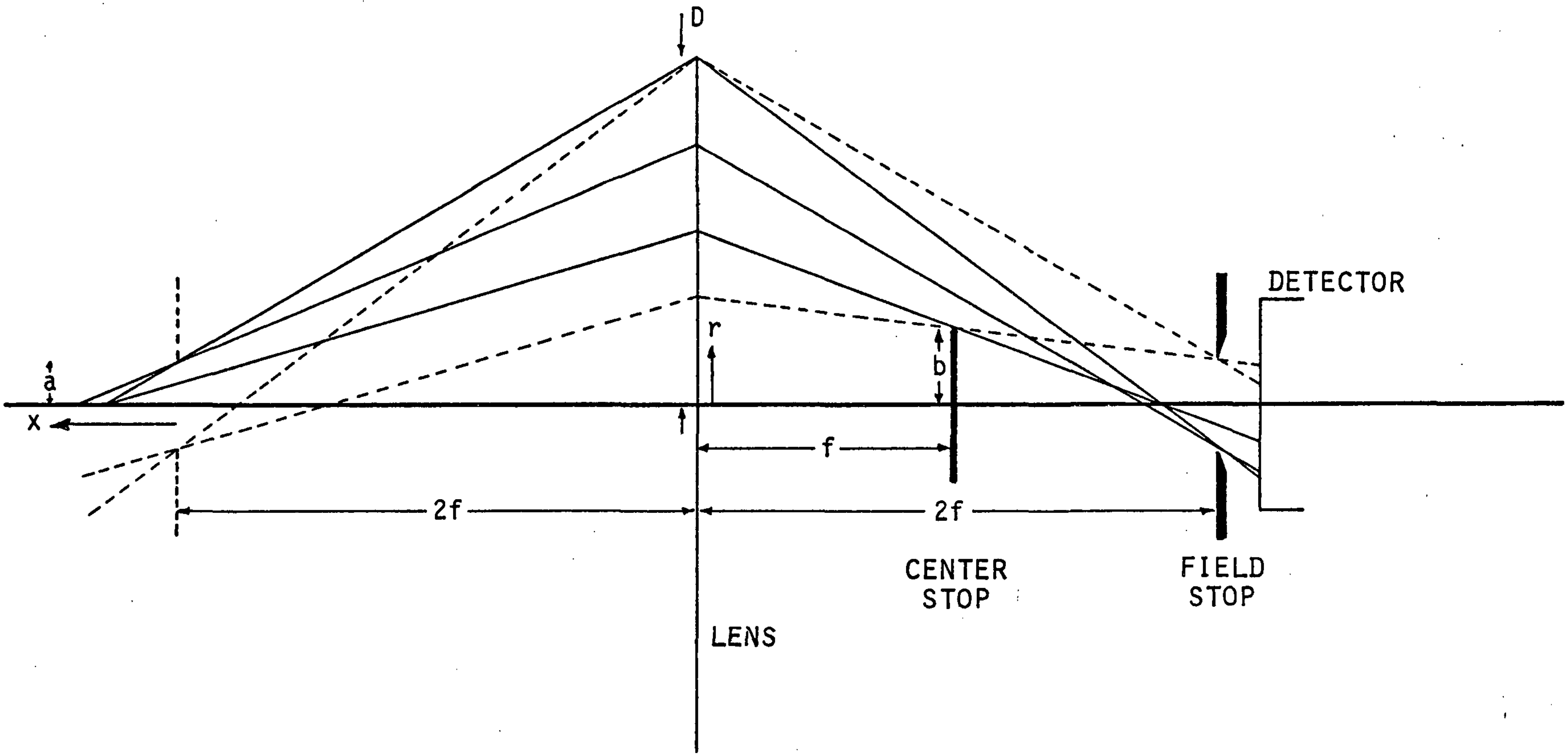

FIGURE 3. SCHEMATIC FOR OPTICAL STOPS.

Table 2. Formulae for Limiting Solid Angles.

Outer Value of Ω.	$\frac{D^2}{(2f+x)^2}$	$\frac{(2f-x)^2}{(2f+x)^2}\frac{a^2}{x^2}$
Valid x Range	$0 < x < \frac{2fa}{D+a}$	$x > \frac{2fa}{D+a}$
Inner Value of Ω.	$\frac{(2f-x)^2 b^2}{(2f+x)^2\ (f-x)^2}$	$\frac{(2f-x)^2}{(2f+x)^2}\frac{a^2}{x^2}$
Valid x Range	$0 < x < \frac{af}{b+a}$	$x > \frac{af}{a+b}$

We may evaluate the expressions in Table 2 for two conditions under which fringe and two spot systems may be comparable.

Table 3. Parameter Specifications.

	Symbol	Fringe	Transit
Receiver Aperture Radius	D (mm)	40	40
Sample Volume and Outer Stop Radius	a (μm)	250	10
Receiver Focal Length	f (mm)	250	250
Inner Stop Radius	b (mm)	10	10

Thus, all quantities except the stop size/sampling volume width are identical in both systems.

Figure 4 shows a graph of the normalized intensity which may be collected from a luminous point on the system axis a distance x (μm) measured in a direction away from the receiving lens, the direction of interest in the rejection of light from walls. The normalization is performed as though the entire receiver could be used. With the addition of a center stop, to permit the center of the lens to be used for the outgoing beams, the plotted efficiency is reduced from its normalized value. Such a center stop is also that which limits the length of the sampling volume to the extent that we show. For comparable optics it is clear that the improvement in sensitive length is from fringe of 6.1 mm to transit of 0.25 mm. This represents a factor of ~25 which is somewhat degraded both by diffraction and residual lens aberrations but is still a very significant improvement. With a small change in optical arrangement for transit systems, the receiver center stop may be made larger than we have shown. The reduction in overall efficiency is then a tradeoff with the reduced sensitive volume length, which may thus be shortened even further.

The quoted collection efficiencies must be taken in conjunction with where the incident light is available to be collected and represent a further increase in the roll-off rate shown. This is simply a factor of $\sim x^{-2}$ for the transit system and $e^{-y^2/2\sigma^2}$ for the fringe system; y/σ is a beam parameter near the waist of the fringe generating beams. Substituting values appropriate to the former example, the 1/e point of illumination intensity along the axis is about 480 μm for the transit system and 17 mm for the fringe system. (This corresponds

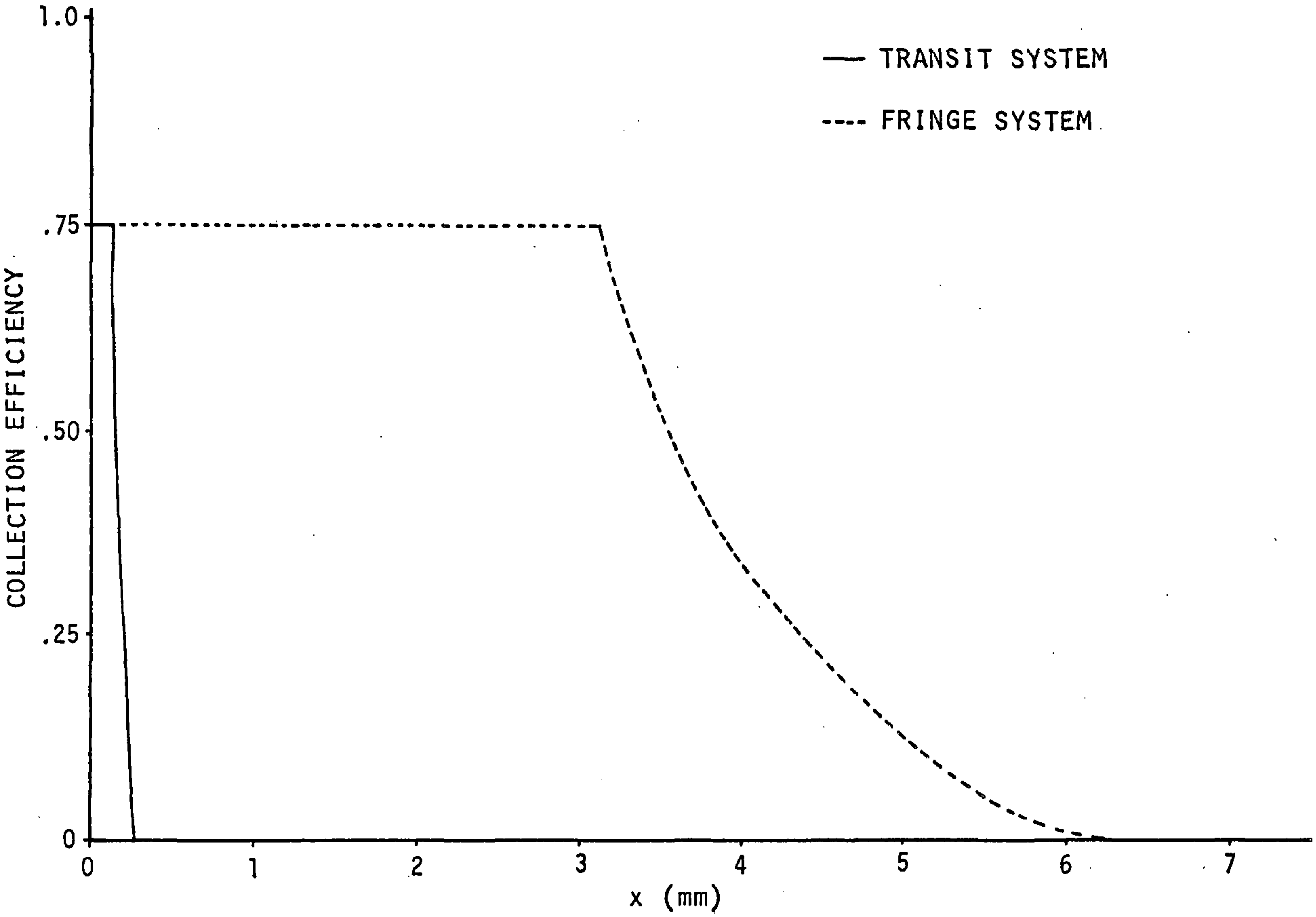

FIGURE 4. AXIAL COLLECTION EFFICIENCY OUTWARD FROM RECEIVER (FROM FIELD STOP IMAGE).

to forty 12.5 μm fringes.) In both cases it is seen to be the receiver aperture which is the critical component.

We have only considered axial properties and it is clear that there will also be contribution to unwanted flare from off-axis positions which receive illumination. The contours of constant flare will be represented by the lines of constant product of the illuminating and receiving hyperboloids, with allowance for the near paraboloidal truncation on axis. This will reduce the efficiency of both systems to a comparable extent since we have supposed that the transit system has been illuminated by a cone not far separated from the inner boundary of the receiving cone, and also that the fringe system is illuminated by beams close to the inner receiver cone boundary but with reduced divergence. It is apparent that these constraints are more serious on the receiver side of the focus which we have not considered here as they do not have a significant effect on wall flare. An analogous analysis could be performed for the receiver side of the sampling volume. This would have relevance to dirty windows. The specular window component must, of course, be rejected by obliquity. In flows with many particles there is some possibility that this effect could limit the maximum tolerable particle concentration.

OTHER ADVANTAGES

For the geometries we have considered, the increase in illumination intensity at the sampling volume is somewhat under a factor of 200 when going from the fringe system to the transit system. Because this makes possible the acquisition of good signals from smaller

particles, the data rate need not fall by a similar factor in a naturally seeded system which may contain more smaller particles.

The observation of a velocity probability in a chosen direction with facility to rotate the spots about an equivalent centroid makes the measurement of shear stress very straightforward. Also because of the small size and large separation of the spots, typically a ratio of 1:25; the measurements of velocity magnitude and direction can both be very accurate.

The system may have the spot rotation arranged without difficult optical alignment by making the output and received images conjugate. It is highly desirable to do this to take full advantage of the foregoing discussion and arrange optimally small stops. For the SDL transit system we accomplish image rotation by use of a mirror Dove of novel design which works at f/4 or a little better without intermediate image and is aberration free in a diverging beam. This makes the whole instrument quite short. One point of interest is the necessity to reject not only scattered light from each beam into its own receiver but from each beam into the other receiver. This is essential, and of course we use two receivers and further stops designed with the above criteria borne in mind. At each point in the optical design the nature and type of stop should be considered -- whether field, aperture or hybrid.

SOME EXAMPLES

Figure 5 shows the approach to a wall with the earlier Rolls Royce system, and Figure 6 shows measurement in a subsonic fan. Both

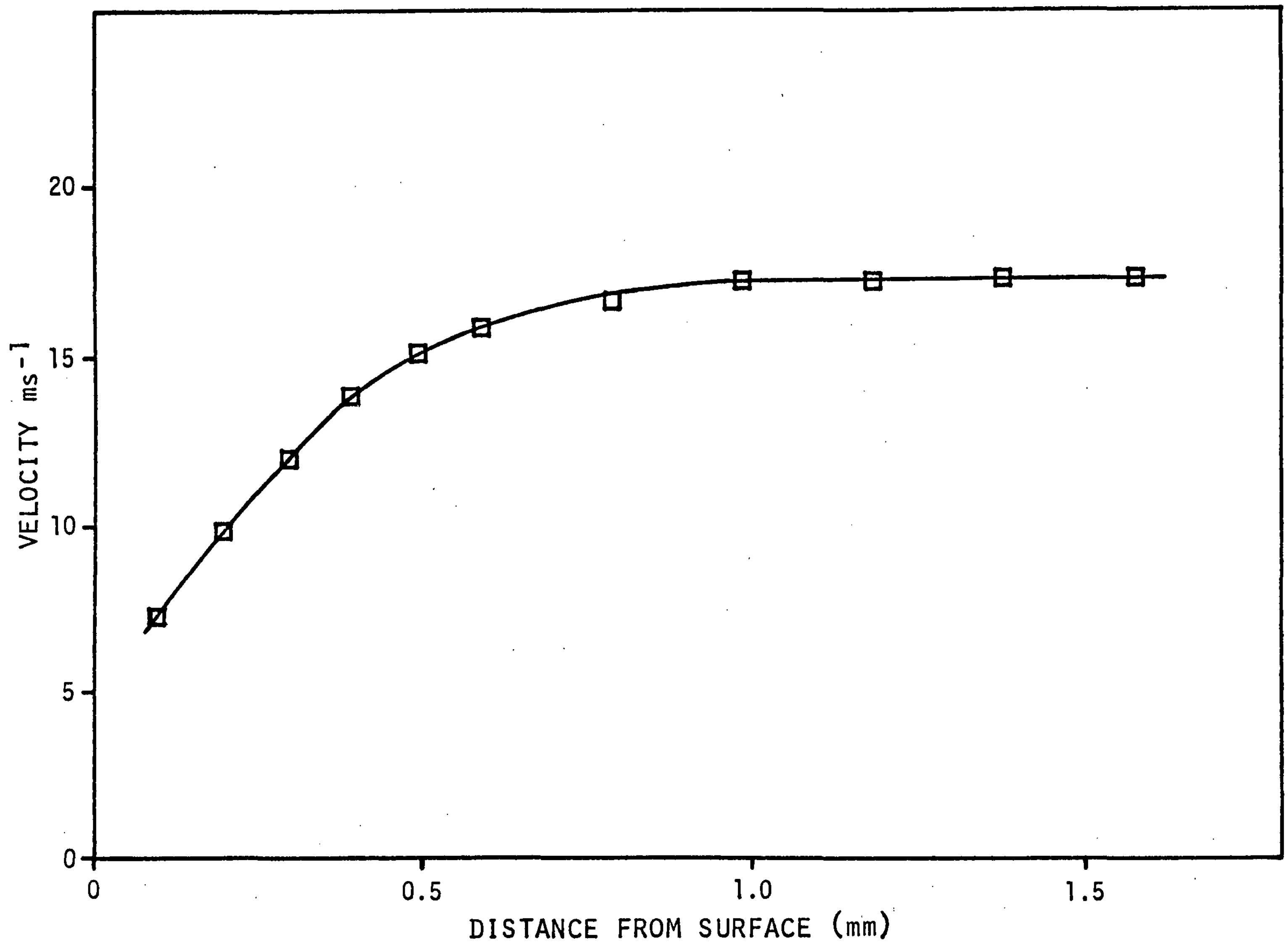

FIGURE 5. BOUNDARY LAYER TRAVERSE ON PRESSURE OF A TURBINE CASCADE.

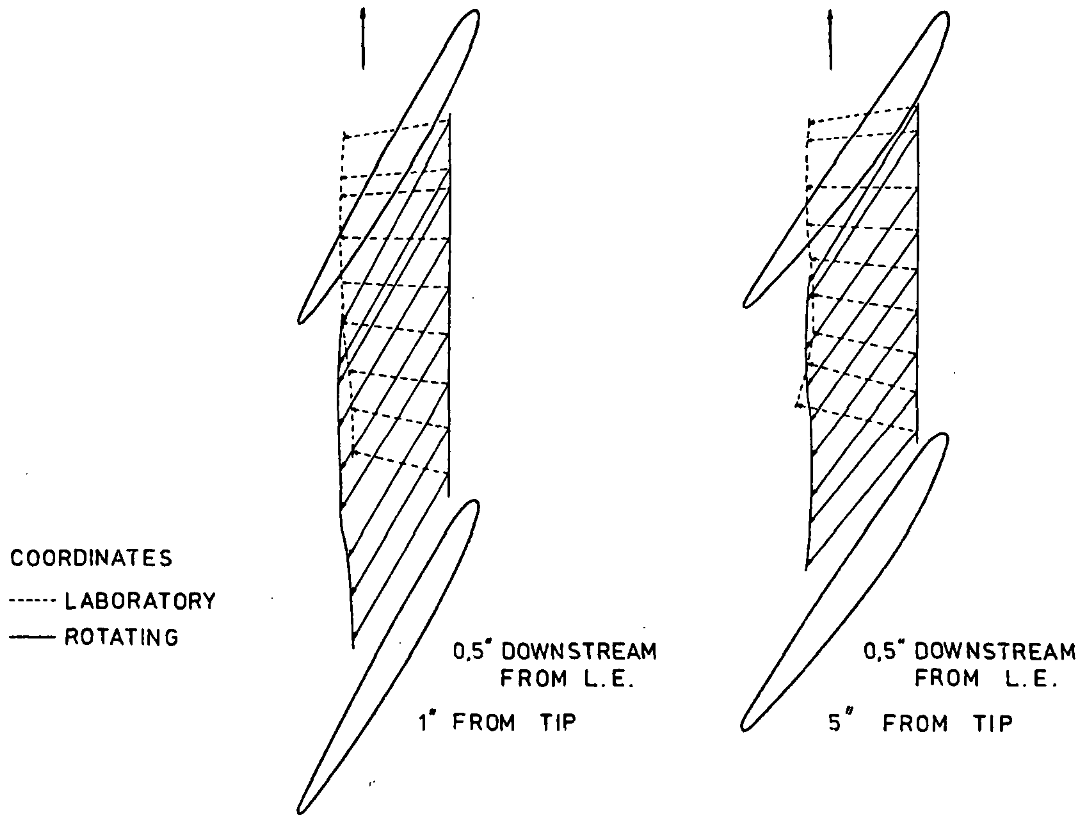

FIGURE 6. INTER-BLADE TRAVERSES AT DESIGN.

figures are only illustrations of system performance which has been substantially improved in the newer SDL equipment.

CONCLUSIONS

1. Flare light can be most satisfactorily rejected by well considered geometrical design and attention to optical components.

2. The transit configuration allows at least an order of magnitude improvement in the proximity to walls at which good measurements may be made, given similar constraints.

3. The capabilities of the transit system to look at smaller particles and measure stresses by spot rotation are especially useful close to walls.

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